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PROGRESS REPORT II

BEARING MATERIALS FOR PROCESS FLUID LUBRICANTS

by

M. B. Peterson

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I. INTRODUCTION

There has been increased demand for bearings to operate under unusual environmental conditions. Because of these environments, it has become necessary to use fluids other than organics. Since almost every system contains other working fluids, it was logical to use these fluids to lubricate the bearings. These fluids are liquid metals, water, molten salts, and a variety of gases. One of the main problems associated with the development of such systems is the selection of suitable materials. Since most of these fluids are non-lubricating it would be anticipated that the major problems would be in those areas where sliding is taking place. This occurs in thermal expansion joints, cams, guides, and control systems. Sliding also occurs on the bearing material at various times. The purpose of this phase of the investigation is to consider the materials which could be used for such applications.

In a previous report(1) consideration has been given to the various problems which might be encountered in water and steam. It was concluded that there were three major problem areas. Corrosion, erosion, and surface damage from sliding. A considerable amount of work has been done on the selection of materials for water and steam environment particularly in high purity water. Consideration was given to the various types of erosion. It appeared to be the major problem in wet steam environment. The approach suggested was to select a material which will have sufficient hardness to resist erosion after the maximum compromises have been made in bearing design. Thus, the problems of erosion are related to a specific design and are difficult to consider in general.

A number of investigations have been conducted on the sliding characteristics of materials in water environment. From these investigations a number of hard, wear resistant materials have been found adequate for sliding applications. These materials have also been successfully used in a variety of applications.

(1) Peterson, M. B. Progress Report - Bearing Material for Process Fluid Lubricants, MTI-62TR20 Contract Nonr 3731(00)FBM.

The difficulties with such materials are that they are inherently poor bearing materials from a number of standpoints. They have high modulus of elasticity and yield strengths which prevents deflections. This lack of deflection can cause problems with shaft misalignments. The area of contact will remain small; surface temperatures are therefore higher and the transition from hydrodynamic lubrication will occur at higher velocities. The hard materials do not tolerate dirt unless they are extremely hard. Hard materials also have generally higher friction which also leads to increased surface temperatures. The only advantage of such materials is that they resist surface damage. The question one asks is whether the softer corrosion resistant materials could not be used. Two questions immediately arise. First, can some means be found to prevent surface damage by means other than hardness and secondly, will this material withstand the temperatures encountered in sliding.

In the previous work a survey was made of the means by which surface damage could be prevented. It was concluded that a number of criteria other than hardness exist for selecting materials.[(Appendix 1)]

An analysis was made of the effect of yield point on the sliding surface temperature.[(Appendix 2)] It was found that the surface temperature was lower (other factors being equal) the softer the material. This is due to the fact that the area of contact was larger. However, it could not be predicted whether this lower temperature was of value or not since the temperature was closer to the melting point. For example, see θ_{max} and θ_{max} % of the melting point for indium and titanium. The real problem is that as yet one is unable to define a θ_F which is the failure temperature for a given set of materials. It may, in certain instances, be the melting temperature or the recrystalization temperature, however, in other cases it may be something else. Thus one does not know the practical significance of the derived temperature with respect to failure. However, it is of significance that the softer materials operate at a significantly lower temperature for example 67°C in the case of indium; 475°C for titanium.

On the basis of these two studies it was concluded that for operation where erosion was not a problem the use of softer materials merited further investigation. Accordingly a selection of corrosion resistant materials

for water or steam was made for temperatures to 500 F or above. A series of low speed friction tests were run on these materials for the following purpose.

(1) To determine the basic mechanism of prevention of surface damage in water and steam and compare it with the results in air.

(2) To determine which of the criteria listed in appendix could be used to select bearing material.

(3) Evaluate some typical material which might be considered for bearing application.

This report outlines the progress to date.

II. SUMMARY

Consideration has been given to the materials which could be used for water and steam lubricated bearings and sliding components for temperatures to 650 F. In this phase of the investigation materials selected on the basis of the various criteria for sliding effectiveness were evaluated in low speed friction tests for their surface damage characteristics. The following results were obtained:

1. For all the materials tested, except iron, very little difference could be detected in the sliding characteristics in water, wet steam, dry steam or air, this permits extrapolation of data obtained in air.
2. The criteria of nonsolubility and formation of soft oxide films appeared to be the most suitable criteria for material selection.
3. Of the materials suitable for use at 500 F, gold gave the least surface damage and merits further consideration for development of soft bearing materials.
4. A wide variety of other materials are available for use as bearing materials or sliding components based on the specific bearing design and operating conditions. (Based on literature survey, and correlation with results for air operation at high temperatures).
5. A low yield point will result in a lower surface operating temperature. This, however, does not necessarily mean less tendency to fail.

III. APPARATUS AND PROCEDURE

In this investigation the apparatus shownin figure 1 was used. Essentially it consisted of a hemispherically tipped rod sliding back and forth on a flat plate. The rod specimen was mounted in the lever arm. This arm was mounted in ball bearings so that one end could be moved in either a vertical or horizontal plane. The flat specimen was clamped to a support table which was rigidly fastened to the base plate. The load was applied with an air cylinder which exerted a known force on the arm directly above the rod specimen. Sliding was obtained by moving this arm back and forth with an air piston at a velocity of approximately 5 ft./min.

In order to measure friction, strain gages were mounted on the arm which connected the piston to the lever arm. The force which the piston exerted on the arm was determined by previous calibration of the system with dead weights. The force was recorded on a Sanborn recorder.

Heat was supplied by resistant heaters mounted in the upper specimen holder andin the lower support table. The temperature was controlled by a thermocouple mounted on the surface of the support table at the same position as the flat test specimen. A container surrounded the specimens in order to insulate them from the air and to provide a reservoir for the steam environment. The steam was supplied to this cavity thru a hole in the upper specimen holder. The point of admission was directly in front of the rod specimen. The steam was prepared in an autoclave by heating distilled water (10 micro-mho cm resitivity). The initial steam was vented to avoid appreciable oxygen content. This steam was supplied in the wet condition by cooling a portion of the supply line. Although this proceedure should eliminate most of the gases from the system it could not be claimed that the tests were oxygen free since a sealed system was not used. Prior to the test the specimens were cleaned using a standard procedure of levigated alumina and water. They were placed in the apparatus and heated in steam to the desired operating temperature.

The test was then started and friction was recorded for one-half hour. In temperature cycle tests the temperature was either raised or lowered in increments; the test was run for 15 minutes at each temperature.

In these tests the following conditions were used:

Load - 30 pounds
Velocity - 5 ft./min.
Temperatures - 80-650 F
Sliding Distance - 1 inch/cycle
Configuration - Hemisphere versus flat plate
Type of Motion - reciprocating.

IV. RESULTS

As a first step in this investigation it was necessary to determine the surface damage in low speed slider experiments with the corrosion resistant materials. First of all, a considerable amount of experience has been accumulated on the surface damage in air. It was desired to know if the presence of water vapor or water drops influenced the frictional behavior. If it doesn't, all this experience can be used in the selection of materials. Secondly, it was desired to evaluate the criteria for the selection of materials. Accordingly, a number of materials were selected based on each different criterion and evaluated in frictional experiments.

1. Comparison of the Frictional Behavior in Wet Steam and Dry Steam with Air.

Although with most metals an oxide would be produced in steam or water vapor, there is little reason to believe that the frictional behavior will be the same with the different environments. Accordingly, a series of tests were run with materials for which air data was available. First, temperature cycle tests were run with Stellite 3 sliding against itself. These data are shown in figure 2. It can be seen that there is very little difference between the results in either air, wet steam, or dry steam. The source of the water also had little effect. A similar series of tests were run with the pure metals Fe, Co, and Cu sliding against themselves. These materials were chosen since they are likely base materials to be used in such environments. These data are shown in figures 3, 4, and 5. Although some dependence on the environment is apparent, these are not considered significant. Similar conclusions can be drawn from the results with tool steel and S-Monel sliding against themselves (figures 6 and 7). Thus it can be seen that, except for minor variations with iron and tool steel, the Frictional behavior is the same in air, wet steam, and dry steam. Observation of the surface damage in each case led to a similar conclusion. It must be pointed out, however, that there is undoubtedly oxygen available to the surface in any case

even though care was taken to exclude it from both the specimens and the water. The point that is made here is that the steam did not modify the frictional behavior. Further experiments in a controlled pressurized environment would be necessary to prove that the reactions with steam itself gave the same frictional behavior as that in oxygen environments.

2. Comparison of the Frictional Behavior in Air and Water.

A similar set of experiments were performed in distilled water in order to compare the sliding behavior in air. Tests were run with tool steel sliding against various materials and with various metals sliding against themselves. The frictional behavior of these materials in water is compared with that in air in figure 8. It can be seen that with the exception of iron and Stellite 3 the friction in water is essentially the same as in air. If the friction is exactly the same it would fall on the 45^{o} slope line. The behavior of iron and Stellite is probably due to the increased reactivity in the water environment. From the data of figure 2 and 3 it can be seen that the transition temperature in air for these materials is very close to room temperature. The increased corrosion of the water may have lowered this temperature slightly. Thus, it is concluded that with the materials considered here there is very little difference between sliding in air and water.

3. Summary

From these experiments it was concluded that for the materials and the water conditions tested, the sliding characteristics were similar in all the environments and that the data which has been accumulated for air can be extrapolated to this environment. This conclusion cannot be generally applied since it is conceivable that under conditions where the water is completely free of oxygen, and where the free energy indicates no reaction, oxides films may not be formed. Under these conditions sliding would be similar to that in an inert environment.

Accepting this conclusion, one can make the following statements as to the mechanisms of surface damage and the selection of materials:

1. Whether surface damage will result or not will be related to the ability of the surfaces to adhere sufficiently and transfer under the action of the combined stress at the generated surface temperature.
2. The above will be modified by the formtion and break down of the surface films, oxides, extruded materials from a two phase system, eutectic films, worked surface material and others, which in essence change the surface material.
3. Quantitatively one cannot predict the conditions under which surface damage will occur. In fact, at the present time one cannot, with certainty, determine the surface conditions.
4. However, based on the discussion in appendix 1, techniques are available for the selection of materials which may slide without surface damage. For an oxidizing environment, the following types of materials may be suggested:

   hard surfaces
   nonsoluble materials
   hard oxide films
   soft oxide films
   self-lubricating
   formation of molten surface films
   eutectic films
   nonmetallic
   hexagonal structure

Some of these may be eliminated based upon the particular problem in hand. Hard surfaces have been investigated in detail and the results published. Further consideration here is for comparison only. In order to form molten surface films, high velocity is necessary. In bearing applications, low velocity slip occurs frequently.

4. Selection and Evaluation of Criteria

Materials were selected based on the various methods of selection previously listed. Many of these materials are not corrosion resistant, but were used to demonstrate the principle. Whereever possible, however, the previously listed corrosion resistant materials were used.

In this investigation primary consideration is being given to bearing materials. Accordingly, it would be expected that sliding would be in combination with a hard material which represented the shaft. At high temperatures, it would be coated with an oxide film. From the previous discussion, from experience with sliding in air, and from corrosion and erosion behavior one would consider a hard cobalt base or ferritic alloy. Two representative materials were chosen as standards in this investigation. These were M-2 tool steel and Stellite 3.

The question arises as to the method of evaluation of these materials. It was not practical to make bearings of the materials even though some of the variables could only be studied in in this manner. Some simpler test must be devised. Consideration of the requirements of bearing materials show that sliding will occur under the following conditions.

a. In initial assembly there will be contact. Damage, however, can be avoided by use of a conventional lubricant.

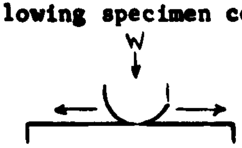
b. During initial start-up the bearing must be "run in" to provide an effective bearing area and to compensate for misalignments in manufacture. Sliding will be at high load and high speeds for relatively long periods of time.

c. In start-up and stop, materials will contact at low pressure and low velocity; contact will be for a short period of time.

d. Dynamic loads will cause contact for a very short period of time at high velocity and low pressure.

e. Oxidation, thermal expansion, or growth will cause contact until sufficient wear has taken place to remove the excess material. Sliding could take place under almost any conditions.

From this it can be seen that failure may result from sliding under two conditions: low speed welding and high speed thermal softening of the material. The primary cause of failure in each case may be the same as that of metal transfer or surface roughening or it may be different, for example by fatigue. However, it is apparant that materials which are damaged by low speed sliding will in most cases not suffice in the high speed case. Furthermore, it is difficult to see how such materials could be used in a bearing. Accordingly, a low speed evaluation was used. In this case the following specimen configuration was used:



The reason for this choice is that it is a more severe condition of sliding for the bearing material. The high pressure is maintained throughout the experiment. Secondly, this configuration

is a better evaluation of the bearing material, particularly where surface films are present. With the specimens reversed the frictional behavior would tend toward the hard shaft material.

Accordingly, an evaluation of a number of materials was conducted to represent the previously listed criteria. Tool steel and Stellite 3 sliders were rubbed against these materials in air, water, and dry steam under the conditions described in the procedure section. These results are shown in Table 1. Here the friction coefficient is given and the surface damage listed as poor, fair, and good. This general classification is sufficient for the present purpose. Good means a polished track, fair means some light score marks and poor means that there is welding transfer or appreciable surface damage of some kind.

It is readily apparent that those materials which formed the softer oxide films and those which did not oxidize gave the best surface finish and the best frictional behavior. Those which formed the soft oxides gave the lowest friction and the noble metals gave the least surface damage. It appeared that the damage with, for example, Co and Cu took place initially until a stable lubricating oxide film could be built up.

Of particular interest is the results with gold. It had by far the best frictional behavior. The friction was low and surface damage nonexistent. Because of these results some further tests were run with gold. These results are shown in the following table:

	f oil	f air	f water
Gold Slider vs Tool Steel Flat	.12	.33	-
Tool Steel Slider vs. Gold Flat	.047	.23	.26
Sn Babbitt Slider vs Tool Steel Flat	.094	.42	-
Tool Steel Slider vs Sn Babbitt Flat	.068	.38	.38

It can be seen that the gold is consistently better than theSn Babbitt from a frictional standpoint. The surface damage was also less in the case of the gold. The tin babbitt surface contained

very fine score marks while, with the gold surface, no evidence of sliding could be detected other than the indentation made by the loaded tool steel hemisphere. The most unusual result is the low friction in the presence of the lubricating oil. It would not be expected that the petroleum fluid which was used would lubricate the gold. It could, however, lubricate the tool steel although such a behavior was not evident with silver as shown below:

Slider	Flat	f Oil	f Unlubricated
Tool Steel	- Silver	.19	.23
Tool Steel	- Gold	.047	.23

Although one might speculate on the reasons for such behavior, such a study is reserved for future work. However, it appears that the nonsoluble criterion is the best of those which were evaluated.

Other types of criteria could be applicable which could not be evaluated because of the low speeds considered. Two of these are those that form molten interface films and those that form eutectic films. An evaluation of these criteria is deferred until higher speed studies are conducted. Self-lubricating materials must also be considered. However, any self-lubricating materials must contain a base material and some sort of a lubricant. One of the properties desirable in the base material is that it, by itself, slide without surface damage. Thus it would be expected that this study would uncover the base material for further work along these lines. However, since some commercial materials are available, it was felt that they should be given first consideration.

Thus, from these data it can be seen that, of the present criteria used, the nonsoluble materials gave the least surface damage. This is represented by the combination of the oxide coated surface and gold or silver. Soft oxide formers, represented by copper, cobalt, and tungsten, also gave only moderate surface damage. For high temperatures the silver and the tungsten can be eliminated for corrosion considerations.

TABLE I

SLIDING CHARACTERISTICS OF MATERIALS

Metal	Bench Tests Frictional Behavior Tool Steel 80 °F Air	Bench Tests Frictional Behavior Tool Steel 80 °F Water	Stellite 500° Slider	Dry Steam Flat	θ_R[1] °f	Soft Oxide	No Oxide	Criterion Non Soluble	Criterion Hardness Brinell	Criterion Hexagonal Structure
Al	f= .84		Poor (f= 1.17)		300	-	-	-	44	-
Co	f= .33 Fair		Fair (f= .28)	f= .27 Fair	-	x	-	-	85-170	x
Cu			Fair (f= .44)	f= .45 Poor	400	x	-	Ta, W, Cr	44	-
Ta			Poor (f= .47)		1868	-	-	-	90	-
Ni	f= .61 Poor		Poor (f= .54)		1100	-	-	-	87	-
Ti			Poor (f= .40)		-	-	-	-	30	x
Zr	f= .56 Poor				-	-	-	-	80	x
Bi					-	x	-	Fe, Co	10-20	x
W			Fair (f= .46)	f= .51	2100	x	-	-	53	-
Au	f= .23 Good	f= .26 Good	Good (f= .35)	f= .5 Good	400	-	x	-	22-58	-
Pt			Poor (f= .61)		-	-	x	-	40-90	-
Ag	f= .23 Good	f= .33 Good	Good (f= .61)	f= .59 Good	400	-	x	Co	24	-
Sn Babbitt	f= .38 Fair	f= .38 Fair								

1. Recrystalization Temperature

TABLE II

SLIDING CHARACTERISTICS OF TYPICAL MATERIALS

Material	Temp °F	Coef. of Friction	Damage Characteristics	
Au	500	.45	Good	No Damage
70-30 Cu Ni	500	.87	Poor	Transfer
90-10 Cu Ni	500	.83	Fair	Transferred Oxide
Phosphorized Cu	500	.43	Good	Transferred Oxide
Pure Cu	400	.41	Good	Transferred Oxide
Leaded Phos Bronze	500	.11	Fair	Transfer
Phos. Bronze	500	.094	Fair	Some Transfer
SAE 64	400	.17	Fair	Some Transfer
SAE 62	500	.68	Fair	
Al Bronze	500	.21	Poor	Large Transfer
Al Bronze (2)	500	.26	Poor	Large Transfer
Wrought Co. Alloy	500	.28	Poor	Transfer
Carbon P658	400	.084	Good	
Carbon 14SC	400	.047	Good	
Carbon 34	400	.15	Good	
Carbon 35SC	400	.047	Good	
Carbon 39SC	400	.028	Good	
Carbon 47SC	400	.047	Good	
Carbon 80	400	.067	Good	
Carbon MY3K	400	.094	Good	
Carbon 72	400	.23	Good	
Plastic 22010	400	.19	Good Swelling	
22078	400	.18	Good Swelling	
16771	400	.14	Good Swelling	
A	400	.19	Good Swelling	
B (Rulon)	400	.13	Very Good	No Damage
Al Bearing Mat	400	.11	Poor	
Du	400	.047	Good	
Graphite Filled Bearing Material 125	400	.19	Good	

V. SELECTION AND EVALUATION OF MATERIALS

Based on the previous discussion, several approaches could be used in the selection of bearing materials. First, one could use gold or copper or their alloys. Secondly, one might use one of the other corrosion resistant materials and devise some means of preventing surface damage. Third, one could use the more conventional materials, plastics, carbons, cobalt base alloys and carbides. The use of one of these approaches will depend to a large extent on the specific application. The plastics and carbon are temperature limited. Cobalt alloys have limited use in nuclear applications. In some applications copper alloys cannot be used because of their tendency to dissolve in and plate out of solution. Since there was no specific application in design, these factors were not used to eliminate materials. Rather a representative group of materials was chosen to represent various types. This included gold, a selection of copper alloys, several cobalt base alloys, carbons and several self-lubricating materials, and several plastics. It should also be pointed out that the materials may not be able to tolerate the environment to which they were subjected nor were they necessarily recommended for these temperatures by the manufacturers. Furthermore, the present list is not considered exhaustive, but rather represents some typical materials for comparison purposes. Sliding tests were run at 500 F using wet steam. These results are shown in table III. It is not intended to go into the details of these tests, but rather to point out the highlights.

1. Of the metals, the gold gave the lowest surface damage; friction is higher than would be desired.
2. Of the copper alloys, the phosphor bronze alloys with or without lead gave the least surface damage and lowest friction. Pure copper also gave relatively little surface damage. The damage appeared to be the result of initial scoring.
3. Carbons and plastic materials were, as would be expected, low friction and low surface damage. The plastic materials gave the lowest surface damage.

4. Only one cobalt base alloy was evaluated. Its behavior was very similar to that of cobalt; low friction, but some evidence of surface damage.

Based on these tests a number of the materials which gave the least surface damage were evaluated through the temperature range. The friction and the surface damage were noted at various temperature levels. These data are shown in the following table. Surface damage resulting from this test is shown in figure 9.

Table III

Frictional Behavior of Several Promising Combinations

Wet Steam Environment

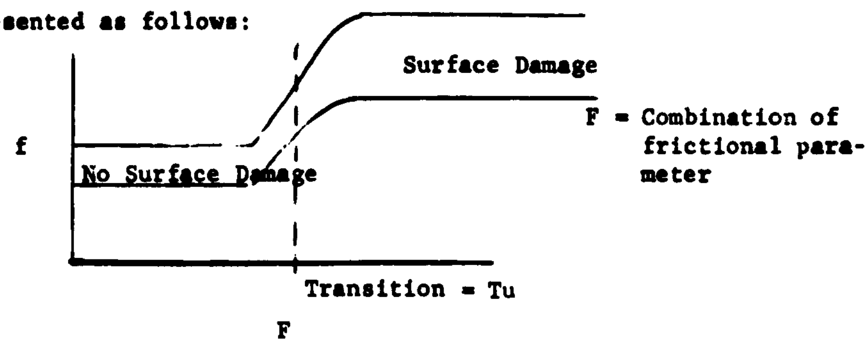
Slider	Flat	f 500	f 400	f 300	f 200	Damage
Stellite 3	Du	.066	.094	.094	.13	No surface damage.
Tool Steel	Du	.072	.072	.11	.11	" " "
Stellite 3	SAE 64	.26	.28	.28	.38	Some transfer.
Tool Steel	" "	.17	.26	.23	.31	" "
Stellite 3	Gatke 125	.22	.19	.23	.23	No surface damage.
Tool Steel	Gatke 125	.19	.22	.22	.19	" " "
Stellite 3	Rulon	.23	Material too soft			No surface damage.
Tool Steel	Rulon	.28	.28	.28	.33	" " "
Stellite 3	G-39SC	.094	.14	.19	.19	No surface damage.
Tool Steel	G-39SC	.094	.11	.12	.13	" " "
Stellite 3	Gold	.45	.50	.52	.38	No surface damage.
Tool Steel	Gold	.42	.47	.38	.33	" " "

It can be seen that the same frictional behavior is maintained throughout the temperature range. From these results as well as the results of previous investigations (referenced in appendix 1) it appears that there are a large number of materials of various hardness levels which could be considered for bearing materials and sliding components depending upon the specific conditions of the application. In addition, a number of techniques are available for further material developments based on data obtained in air and knowledge of the sliding characteristics of material.

APPENDIX I

SELECTION OF UNLUBRICATED SLIDING COMBINATIONS BASED ON SURFACE DAMAGE

When one material slides against another, it is generally found that there is either no surface damage or it is severe. In the first case, sliding is characterized by steady friction values and a polishing of the surface. The second case is charac'erized by welding and transferring of material, erratic friction, usually high, and seizure with closely fitting machine surfaces. Using friction as a method of illustration, this may be represented as follows:



Wear could not be so represented since some materials which are effective in sliding can wear very rapidly. The transition between the two types of sliding can be brought about by a change in material in any given application or a change in operating condition.

The desirable approach would be to calculate T_u from the materials properties and operating conditions. One could then select or develop materials simply for any given application. Unfortunately, this is not possible since different mechanisms can cause this transition. Even if it was unique, it would be difficult to calculate since some of the fundamental quantities of sliding (such as area of contact and surface temperature) are not completely defined. However, many of the factors which influence this transition are known. Essentially, it has been suggested (A1) that surface damage will result if the adhesion of the two materials becomes high with regard to the strength of the material that is $T_w = f\left(\frac{\text{adhesion}}{\text{mechanical strength}}\right)$. This ratio can be effected by a large number of variables, but primarily failure is caused by one of the following conditions:

1. Welding of the surfaces at the generated surface temperature
2. Metal transfer from a variety of causes.
3. Break down of surface films which prevent welding.

Although one might use the above considerations to hypothesize what materials will be effective in sliding contacts, a number of means are available based on the material properties and the operating characteristics. At the present time, these are the best criteria for the selection of materials. They will be discussed separately.

1. Solubility

It has been shown (A2) that the solid solubility of the couple is a suitable indicator of the adhesion. For example, silver sliding against itself gives high friction and surface damage while silver sliding against steel gives low friction (.45) and very little damage. One could then select materials for sliding contacts which have low solubility if the material themselves will withstand the loads. Data on the solubilities is given in reference A3 and can be applied to the potential metals for only Cu, Bi and Ag.

It should also be pointed out that the solubility of metals in oxides is much more restricted. Thus, metals sliding against oxides, carbides, etc., have much greater potential than metals versus metals. Since oxide formation is expected the noble metals appear particularly promising. This, of course, does not mean that all non-soluble metal combinations will all be effective in sliding since other factors such as the formation of surface films and generated surface temperatures may significantly alter the results. The limited solubility of copper, silver, and bismuth in cobalt and iron may be useful in combining materials.

2. Formation of Oxide Films

Most of the commonly used materials depend upon the formation of oxide films to prevent damage in sliding. If an oxide can be maintained between the sliding surfaces, friction, wear, and surface

damage will be reduced. The following data gives the transition temperature for conversion from poor sliding characteristics to effective sliding (ambinet for low speed, light load sliding of several base materials and alloys):

Material	Transition Temp $^{\circ}$F (A4)
Fe	100-200
Cu	400-500
Ni	1200-1400
Mo	800-900
Cr	800-1100
Inconel X	1000-1200
Hastelloy B	500
S Monel	400
1020 Steel	200

Similar types of alloys or minor modifications in composition do not affect the transition temperature greatly. An increase in the load or a decrease in velocity tend to increase the transition temperature. This information and considerably more have been accumulated on the sliding of unlubricated contacts in air. It would advance the knowledge of water and steam lubrication considerably if a correlation could be established between the effect of the oxide formed in air and that formed in water or steam.

3. Formation of Soft Oxide Films

If a soft oxide or other film such as chloride is generated on the surface, sliding will be significantly improved if the wearing away of the oxide does not increase wear significantly. A soft or plastic film has the added advantage in that it is much more difficult to remove from the surface and, therefore, will suffice over a broader range of operating conditions. The hardness of some of the softer oxide films are given below (A5):

Oxide	Moh Hardness
Bi_2O_3	2
Sb_2O_3	2.5
CdO	3
Co_3O_4	-
CuO	3
PbO	2
SrO	3.5
WO_3	2.5
ZnO	4.0
$PbMoO_4$	3
$PbWO_4$	4
$CuWO_4$	4.5

Many other types of surface reaction films would be expected to be soft. Generally, this can be related to their structure, melting point, or atomic size of the components. In general, it is known that the following more common materials are soft compounds.

Halides
Hydrated Oxides
Sulfates

However, consideration must be given to the erosion of such films.

4. Hardness

It is well known that hardness is one of the best criterion for sliding effectiveness. A hard material combination is not only good in itself but retards the removal of any surface film. It has been shown that two hard surfaces will even slide effectively after all surface films have been removed by heating in vacuum. It is not possible as yet to define a specific hardness necessary because of the influence of the other factors of adhesion and surface films. However, the recrystallization

temperature may be considered as the point where marked softening will occur and the surface damage will increase significantly. Recrystallization temperatures for the materials are listed in Table 1.

5. Self-Lubricating Materials

Many materials contain solids which are known to be effective solid lubricants. In operation, this film will spread out across the surface and prevent surface damage. Examples of this type of material are the leaded bronzes, carbon graphite, and porous materials infiltrated with soft metals. However, the same phenomenon is known to occur with several materials where there is a second soft phase, even through it is not added intentionally. Examples of this are the metal binder in the carbides and in silicon containing alloys (A6). Although there is little data on which to make a choice of these materials, it is felt that there is considerable promise here particularly in the development area.

A bibliography of self-lubricating materials have been published (A7). A survey of such materials has been made (A8) in reference to water lubricated bearing materials. Based on their survey, Nudelman and Sump selected a metal bonded carbon and a Teflon impregnated stainless steel for development. In successive experiments these materials were shown to operate successfully under certain conditions.

The major difficulty with this approach is that the combination of a soft lubricant and a hard matrix would be subject to erosion of the soft phase. The use of such an approach is considered doubtful.

6. Molten Interface Films Generated by Sliding

It has been shown that when sufficient energy is generated by sliding, a soft or molten film will be formed on the surface and effective sliding will result (A9). Sliding on ice is an example of this phenomenon although it has also been shown to be true for metal combinations. This principle could also be applied to thin films. A difficulty in applying this principle

results from the lack of information on surface temperature with solid films as lubricants. Difficulties are also experienced in running at low speeds with such materials. However, this approach may be an optimum solution to the erosion problem which might result with soft films.

7. <u>Hexagonal Crystal Structure</u>

A number of the hexagonal metals have been shown to have better sliding characteristics than would be expected based on other criterion (A10). However, there is insufficient data available to determine if a true transition is observed. A list of the hexagonal metals is shown in Table 1. It should also be mentioned that a number of these metals are known to have poor sliding characteristics.

8. <u>Eutectic Films</u>

In sliding, two surfaces may form at their interface a low melting point eutectic film (if such a compound exists) which will shear in preference to the base materials and thus prevent surface damage. Very little data is available as to how effective such films might be.

9. <u>Metallic, Non-Metallic Combinations</u>

In selecting materials for sliding applications, one should always consider the possibility of using a non-metallic bearing material in conjunction with a metal shaft. The advantages of such combinations include:

1. Elimination of most adhesion and welding problems.
2. Good performance under marginal lubrication, or even dry conditions. This is true of course only when the bearing material has some inherent self-lubricating ability. Such bearings have proved to be particularly good where lubricants such as fuels, water or cryogenic fluids must be used.

3. A faster transition from boundary to hydrodynamic conditions when speeds and loads permit this transition to occur.
4. The possibility of obtaining better damping characteristics.

Among the non-metallic bearing materials which have been used successfully, filled Teflon, nylon, metal-graphite powder compresses and the carbon-graphites are probably the best known although other new materials are now becoming available.

The major disadvantages of all these materials are:

1. Thermal expansion characteristics which are widely different from those of the shaft material.
2. Relatively poor thermal conductivity.
3. The possibility of dimensional instability in certain environments, particularly the high humidity.
4. A general lack of comprehensive design data and experience on the part of potential users.

10. Previous Work

A considerable amount of work has been done on the selection of materials for water lubricated bearings. This work was reviewed in order to answer certain questions:

1. What materials have been found to be effective.
2. Are the oxide films formed sufficient to prevent damage.
3. Is the sliding behavior similar to that in air.
4. Extent of damage in sliding.

A summary of previous work (A11-A13) has been given in the Corrosion and Wear Handbook (A14). First of all, it has been concluded that the soft yielding bearing materials (presumably lead and tin) are not suitable for service in oxygenated water. Efforts have been primarily directed toward hard wear resistant materials. It has been found that order of preference of materials from a sliding standpoint is as follows:

1. Nitrided Stainless Steel
2. Chrome Plate
3. Cobalt Alloys
4. Martensitic Stainless Steels
5. Age Hardened Stainless Steels

It is the author's experience that this list in approximately this order could be compiled from high temperature sliding data in air. Friction coefficients have been reported by Dewees (A15) and Nudelman and Sump (A16). Much of this data is not directly comparable with high temperature air data; however, the friction values at low speed with Stellite 1 in reciprocating motion have been reported to increase from .25 to .48 as the velocity increased from 7 to 27 ft/min. The same value has been observed with Stellite when oxides are formed at high temperatures.

Various bearing tests have been conducted with the previously listed materials to ascertain their effectiveness as bearing materials. Journal bearing tests have been conducted at 15 psi in 150 ^{o}F water (A17). It was found that for water applications a number of bearing materials were satisfactory (carbons, metal impregnated carbons, copper lead bearing materials, bronze, and carbides); however, for steam only silver impregnated carbon was satisfactory. Journal bearing tests were also reported by Battelle (A18). Bearing tests were run with 1-1/4" x 1" and 2-3/4" bearings at speeds to 10 ft/sec. loads to 200 psi. and temperature of 200 F. In general, the ceramic materials were the most promising when tested against Stellite Star J and tungsten carbide. The following combinations were listed as most promising:

Al_2O_3,B_4C - Star J
B_4C,Al_2O_3,B_4C - Silver Lead Plate - WC-TaC-
Silver Lead Plate, Formica FF55, 67,Al_2O_3 - WC
Formica - Chrome Plate

In reference (A14) similar tests are summarized as reported in ref. (A19). In addition to those listed above, carbon graphite with malcomized 17-4 ph and chrome plate are also listed as satisfactory.

Similar results have also been obtained in thrust bearing studies. They demonstrated the superiority of the Stellite, tungsten carbide, and aluminum oxide combination. In pump bearing tests (A20-A21) the best combinations were the carbides, bronze, leaded bronze, and Teflon. It was further reported that most metal combinations galled and the plastics melted.

In some specific studies, oxidized zirconium has been reported to give very good results as a bearing material (A22). Gold alloys have been used in chemical process pumps (A23) containing nitric acid solutions.

TABLE A1

SUMMARY OF PROPERTIES

Corrosion Resistant Materials	Hardness Brinell	Corrosion					Thermal		Sliding					
		Effect on Corrosion												
		Temp.[1]	O_2	Cl	CO_2	SO_2	Thermal Conduct.	Melt. Point	Fe	Soft Oxide	No Oxide	θ_R[2] °F	Solubility	Hexagonal Structure
Al	44	400	-	yes	yes	yes	98	1070				300		-
Cr	-	400	yes	yes	O_2+CO_2							-		-
Co	85-170	500	-				-	2723		x		-	-	x
Cu	44	400	yes		yes	Severe Effect	211	1960	Fair	x		400	Ta(Co) W,Cr	-
Ta	90	500	-		ph<8	Poor	32	5425				1868	-	-
Ni	87	500	-		yes		35	2620				1100		-
Ti	30	650	some				9.8	3135				-		x
Zr	80	650	-				9.6	3335				-	-	x
Hf	98	500						3400				-	-	x
Bi	10-20	?							Good	x		-	Fe, Co	x
W	53	?					96	6152		x		2100		-
Au	22-58	650	-				172	1945		-	x	400	-	
Pt	40-90	500	-				42	3224		-	x		-	
Ag	24	250++					242	1761		-	x	400	Co	
Tin Babbitt	10-20	?	yes				37		Fair				Fe	

1 Estimated maximum useful temperature

2 Recrystallization Temperature

APPENDIX II

ON FAILURE TEMPERATURE IN BOUNDARY LUBRICATION F. F. Ling

The maximum steady-state, surface temperature, $(\sigma_1)_{max}$, of a semi-infinite solid, whose surfaces are insulated everywhere except a constant heat flux, q, is applied over an area $2b \times 2\ell$ is

$$(\sigma_1)_{max} = \frac{2q_1 \; \ell \; F\,(b\ell)}{\pi \; K_1} \quad , \quad F\,(b\ell) = \mathrm{swh}^{-1}\,(b/\ell) + (b/\ell)\;\mathrm{swh}^{-1}(\ell/b) \tag{1}$$

where K_1 is the thermal co iuctivity which is assumed constant.

The maximum quase'-stationary, surface temperature, $(\sigma_2)_{max}$, q a moving semi-infinite solid, whose surfaces are insulated everywhere except a constant heat flux, q_2, is applied over an area $2b \times 2\ell$ which moves along the direction of ℓ with velocity V, is *

$$(\sigma_2)_{max} = \frac{2 \quad 2 \; \ell \; q_2 \qquad \alpha\pi/V\ell}{\pi \; K_2} \tag{2}$$

where α and K_2 are the thermal diffusivity and conductivity respectively, both are assumed constant.

Letting $q_o = q_1 + q_2$ and matching $(\sigma_1)_{max}$ to $(\sigma_2)_{max}$.,

$$\sigma_{max} = \frac{fWV}{2b \;\; \pi K_2 \;\; \frac{V\ell}{2\pi\alpha} + \frac{K_1}{K_2} \;\; F(b/\ell)} \tag{3}$$

where $\frac{fWV}{4b\ell}$ have been substituted for q_o, f being the coefficient of friction and W being the normal load.

Note in equation (1), that when $b/\ell \quad \infty$, so does $F(b/\ell)$. This means for b/ℓ sufficiently large and V sufficiently large

$$\frac{V\ell}{2\pi\alpha} >> \frac{K_1}{K_2} \quad F(b/\ell) \tag{4}$$

is very plausible for most material pairs. Supposing that (4) is satisfied, Then (3) is reduced to

$$\sigma_{max} = fWV/2b\pi K_2 \;\; \frac{V\ell}{2\pi\alpha}$$

---

*F. F. Ling, Zeit. Angw. Math. Phyk., X, 469 (1959)

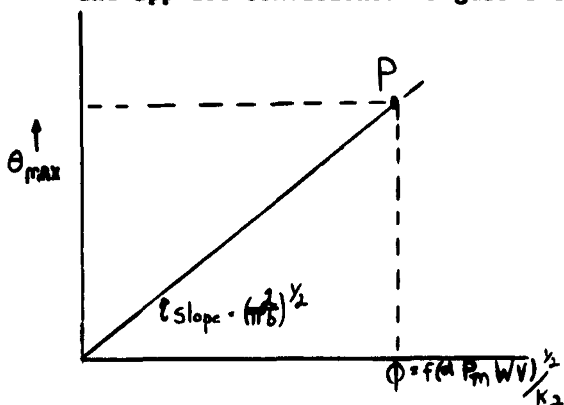
For an experimental set-up in which b is kept constant and the dimension ℓ is governed by plastic deformation of the contact area,

$$4b\ell\ p_m = W \tag{6}$$

where p_m is the yield pressure. Using (6) in (5),

$$\sigma_{max} = (2/\pi b)^{\frac{1}{2}}\ .\ \ f(\alpha p_m WV)^{\frac{1}{2}}/K_2\ \equiv\ (2/\pi b)^{\frac{1}{2}}\ \phi \tag{7}$$

Note the square-bracketed quantity is a function of the material property and applied conditions. Figure 1 shows a plot of σ_{max}. B. ϕ. Of course σ_{max} vs ϕ is a linear function of slope $(2/\pi b)^{\frac{1}{2}}$ which is fixed once the experimental configuration is fixed. In a given experiment, W and V may be changed for a given pair of material so as to increase. Thus σ_{max} will increase as specified by the proportionality constant $(2/\pi b)^{\frac{1}{2}}$. Let P be a point on the curve which represents failure of boundary lubrication which is defined in some way, then the value of σ_{max} will be designated σ_f for the material pair at the operating condition.



Now, define

$$\psi\ =\ 2f^2\ \alpha\ p_m\ W_f V_f/\pi b K_2^{\ 2}\ \sigma_f^{\ 2}\quad \frac{1}{2}$$

which is dimensionless. W_f and V_f are the values of W and V at failure. It is merely equation (7) divided by $\sigma_f = \sigma_{max}$. Theoretically $\psi = 1$, but practically ψ may be different from unity. However, using various materials and various combinations of applied conditions, a range of ψ may be determined. If ψ stays essentially constant, then the assumed model may be said to be good and ψ will be a good universal constant.

Slider Material	ρ	m.p.	C	K	P_m	α
Al	2.7 gm/cm^2	660°C	.215 cal/gm°C	.53 cal-cm/cm^2°C sec	3250 Kg/cm^2	.912 cm^2 sec.
Co	8.85	1495	.099	.165	8900	.195
Cu	8.96	1083	.092	.941	6450	1.15
Au	19.3	1063	.0312	.71	6350	1.18
In	7.31	156	.057	.057	90	.14
Pb	13.4	327	.031	.083	280	.2
Ni	8.9	1453	.105	.22	2000	.236
Pt	21.5	1769	.031	.165	5000	.244
Re	21	3180	.033	.17	9700	.245
Ta	16.6	2996	.034	.13	7056	.23
Ti	4.51	1668	.124	.046	4250	.082
Zr	6.5	1852	.067	.211	10000 / @1400°C 1000	.485

αp_m	$\sqrt{\alpha p_m}$	Ks	$30\sqrt{\alpha p_m}$ *	$\sigma_{max} = 30\sqrt{\alpha p_m}/K$	σ_{max} -% m.p.	Slider Material
2960 Kg/sec.	54 Kg/sec	13.4 Kg/°C sec	1620	121°C	18	Al
1740	42	4.2	1260	300	20	Co
7410	86	23.5	2580	110	10	Cu
7500	87	17.9	2610	146	14	Au
13	3.6	1.5	100	67	43 *	In
56	7.5	2.1	225	107	31 *	Pb
470	22	5.5	660	120	8	Ni
1220	35	4.2	1050	250	14	Pt
2380	49	4.3	1470	342	11	Re
1620	40	3.3	1200	360	12	Ta
350	19	1.2	570	475	28	Ti
4850 / 485	70 / 22	5.4	2100 / 660	390 / 120	23 / 6	Zn

* 30 came from the following: f = 1, W = 1 Kg, V = 1500 cm/sec , b = 1 cm

$$f\left[\frac{2WV}{\pi b}\right]^{\frac{1}{2}} = \left[\frac{2\ (1)\ (1500)}{\pi\ (1)}\right]^{\frac{1}{2}} \simeq 30\sqrt{Kg/sec}$$

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Fig. 1 Friction and Wear Test Apparatus for Oscillating Sliding under Conditions of Heavy Load, Low Speed and High Temperature

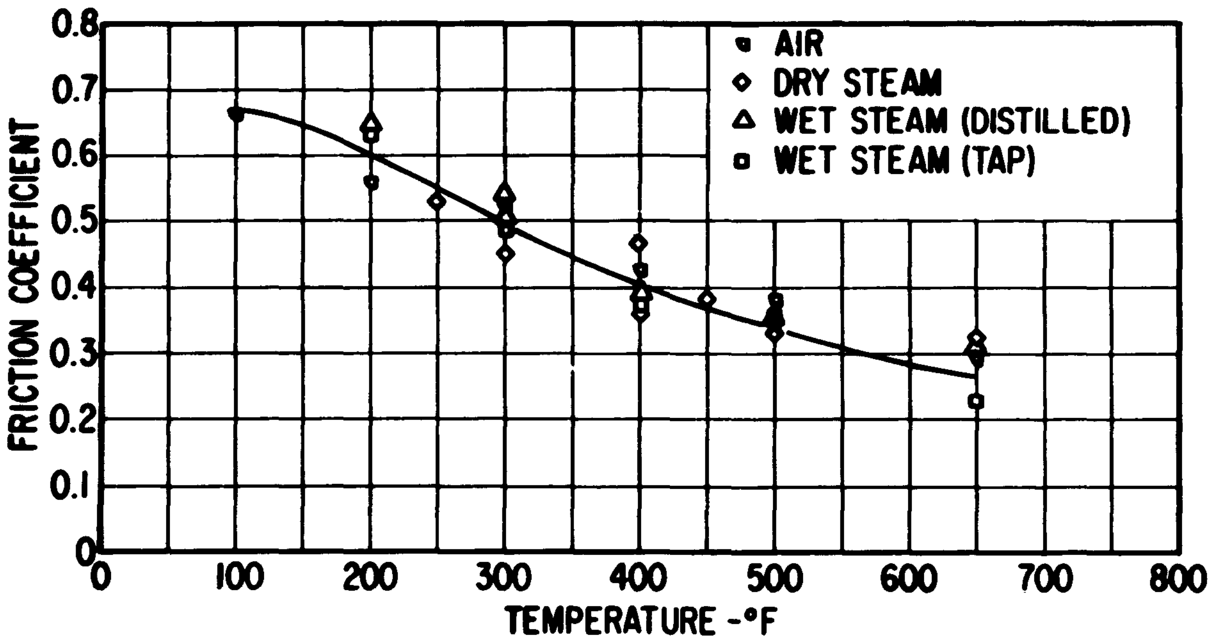

FIG. 2 STELLITE-3 vs STELLITE-3

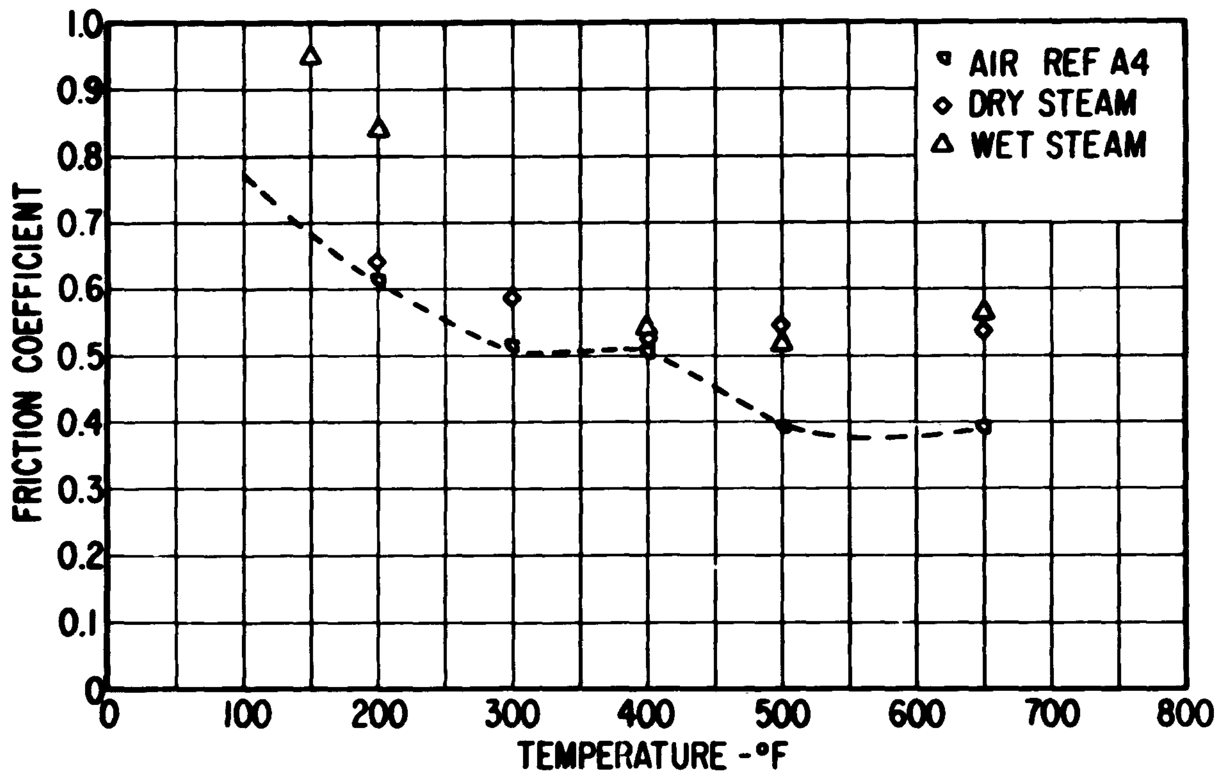

FIG 3 IRON vs IRON

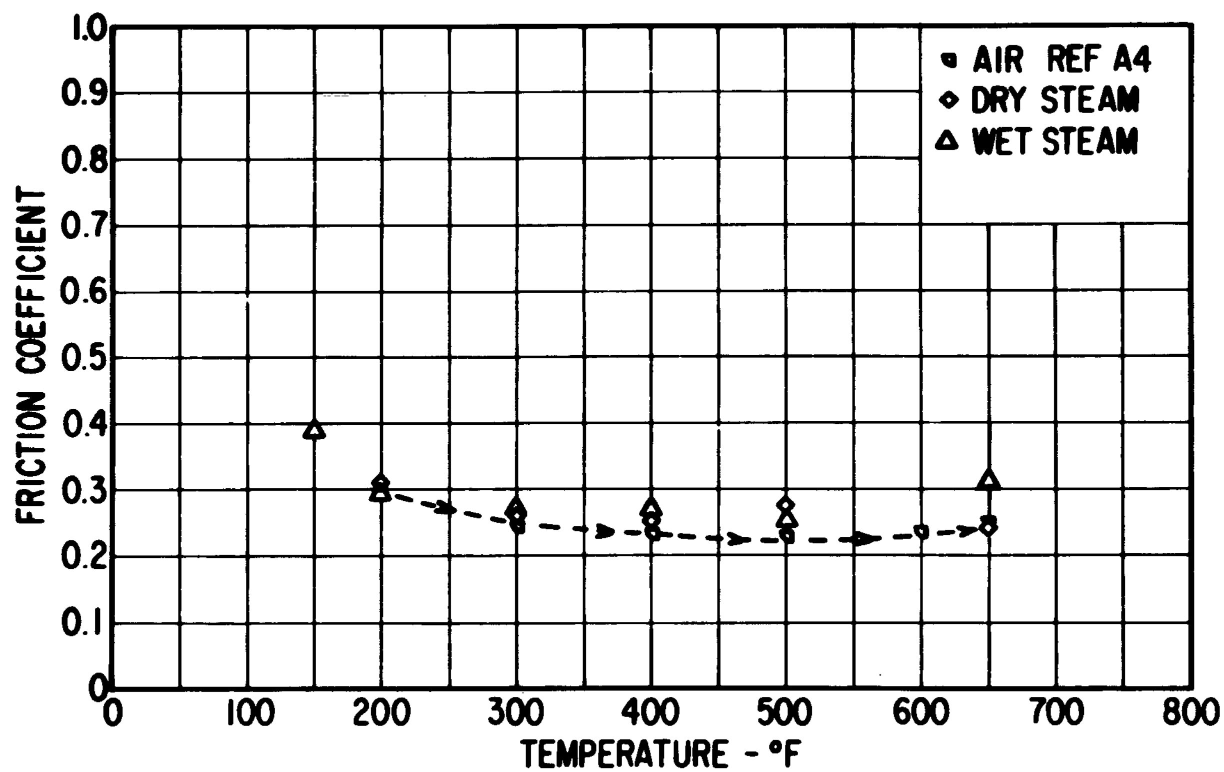

FIG. 4 COBALT vs COBALT

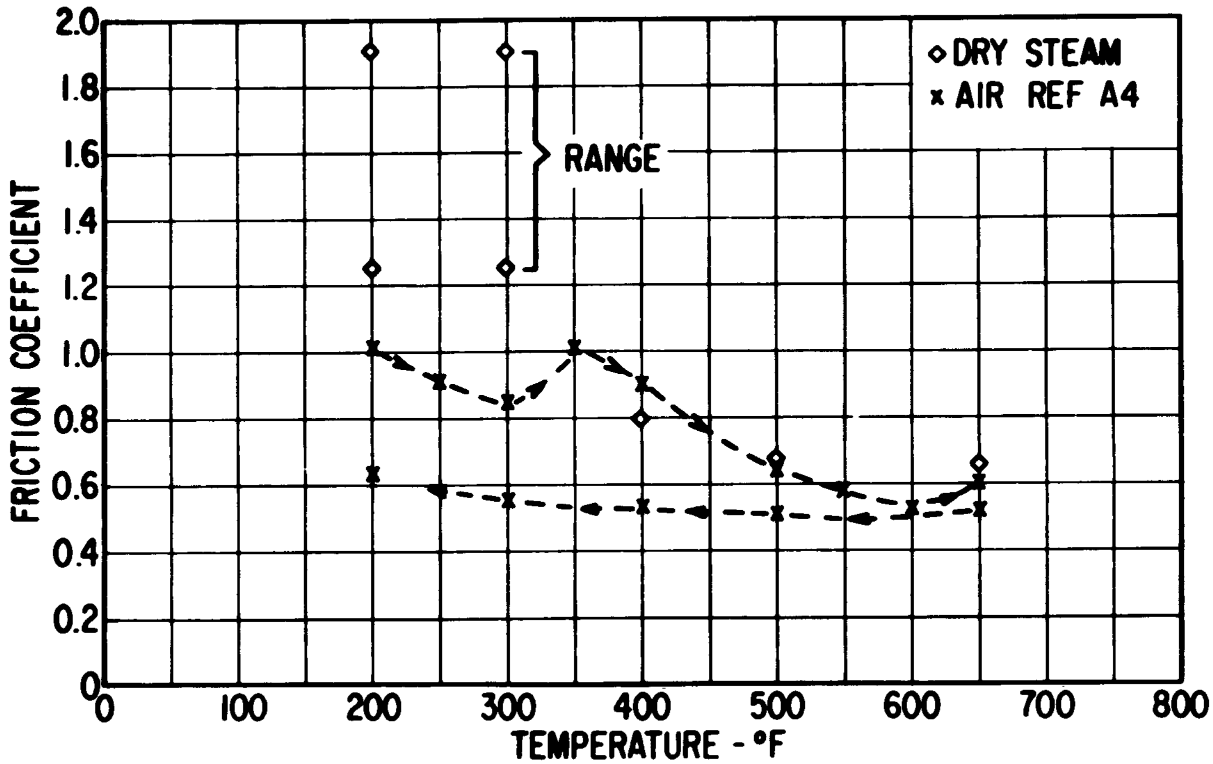

FIG. 5 COPPER vs COPPER

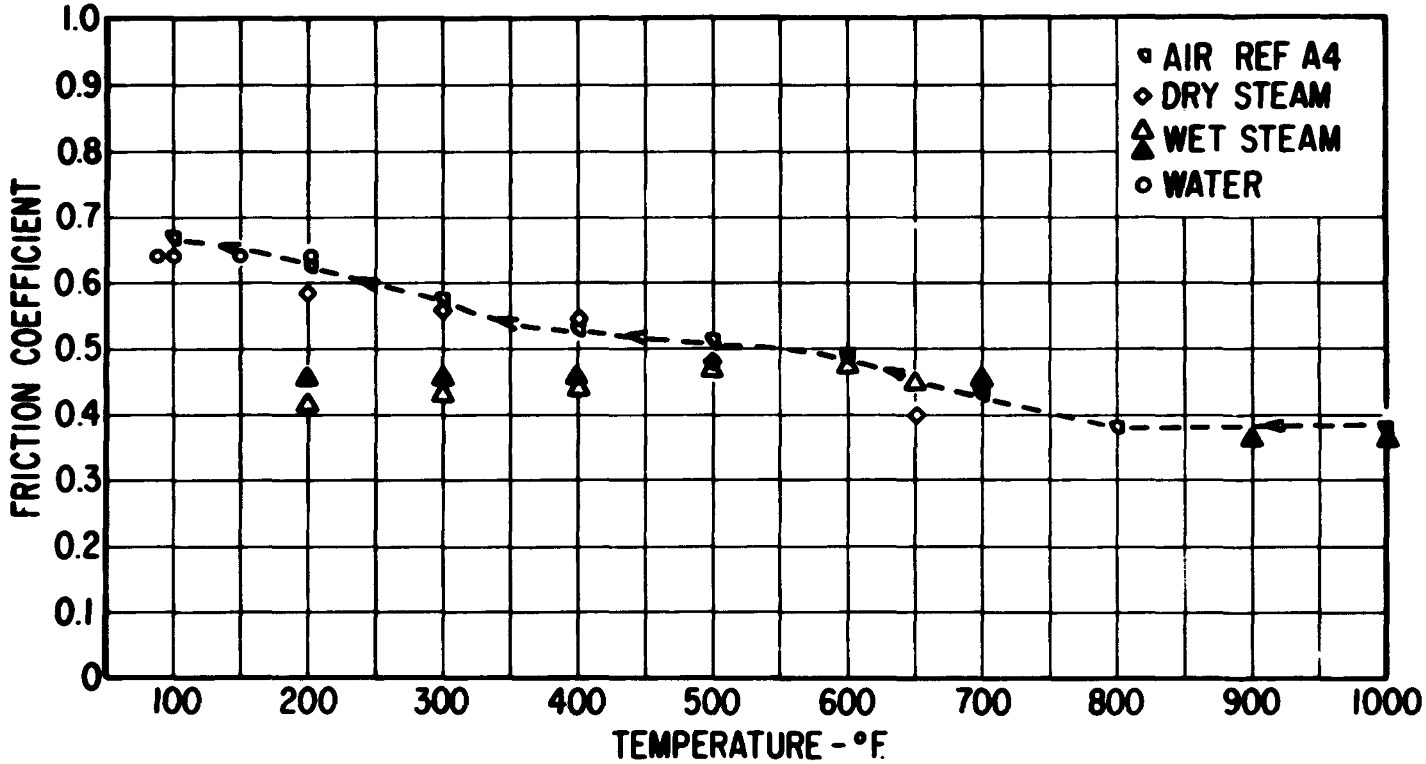

FIG. 6 TOOL STEEL vs TOOL STEEL

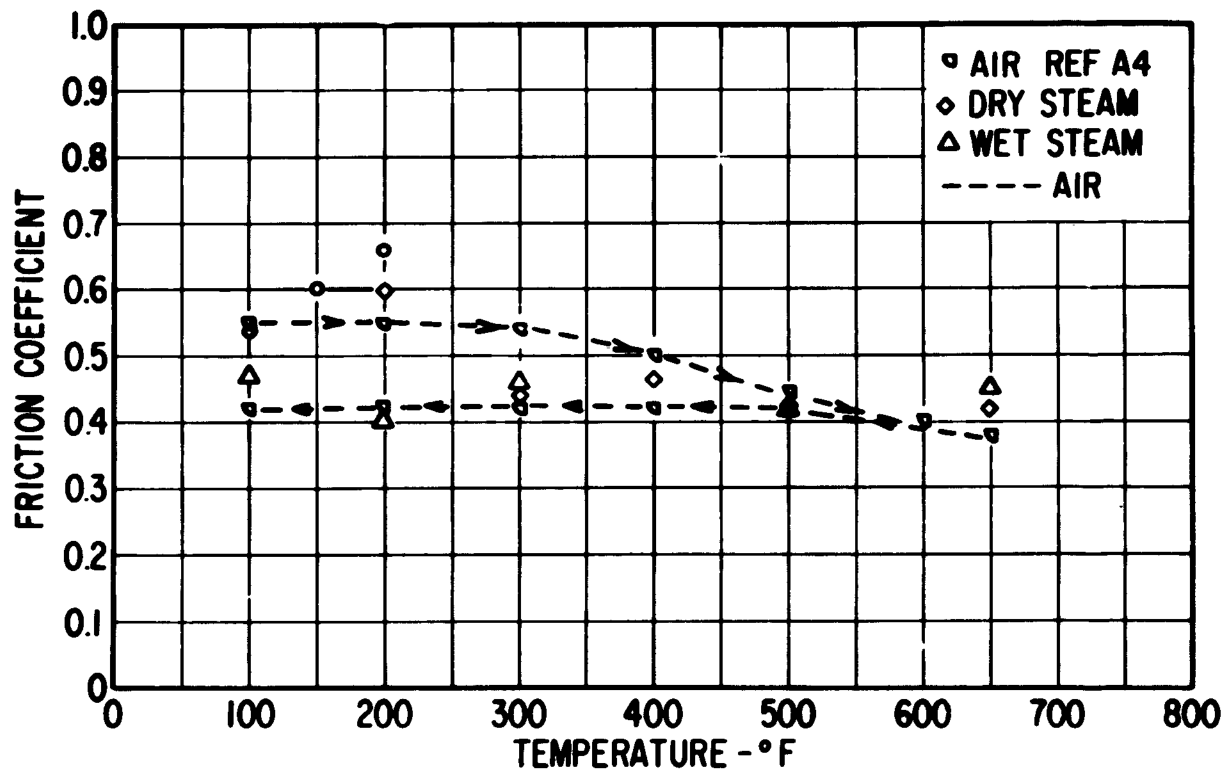

FIG. 7 S-MONEL vs S-MONEL

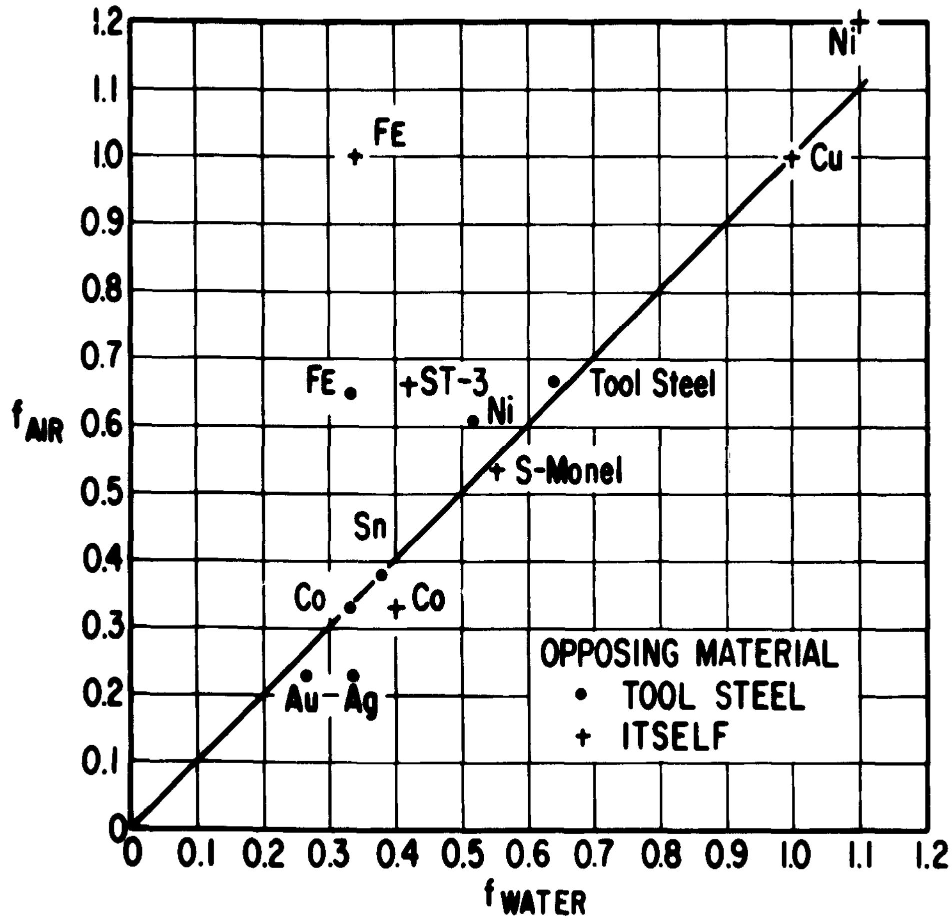

FIG. 8 COMPARISON OF FRICTION IN WATER AND AIR FOR VARIOUS MATERIALS

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April 15, 1963

Dear Sir:

Our recent report (MTI 63TR8) entitled "Progress Report II - Bearing Materials for Process Fluid Lubricants" by M.B. Peterson was incomplete. The figure attached to this letter was inadvertently omitted by the binders (or"bounders"). Please insert Figure 9 in each copy delivered to you.

We regret this error and any inconvenience caused you.

Sincerely,

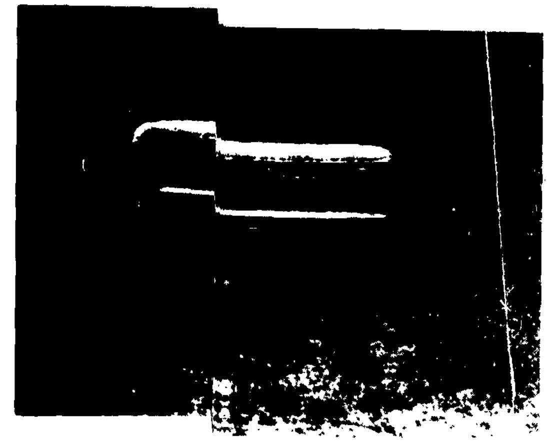
B.E. Earls

B. E. Earls
Technical Editor

BEE/rp

enclosure

(a)



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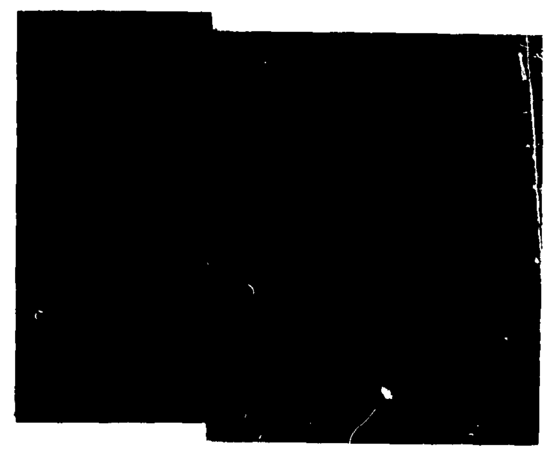

(d)

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Figure 9